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Scrape-off layer plasma and neutral characteristics and their interactions with walls for FNSF

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ABSTRACT

Simulations of the heat flux on plasma facing components from exhausting core plasma are reported for two possible Fusion Nuclear Science Facility (FNSF) divertor configurations. One configuration utilizes divertor plates strongly inclined with respect to the poloidal magnetic flux surfaces like that planned for ITER and results in a partially detached divertor-plasma. The second configuration has divertor plates orthogonal to the flux surfaces, which leads to a fully detached divertor-plasma if the width of the divertor region is sufficient. Both configurations use scrape-off layer impurity seeding to yield an acceptable peak heat flux of $\sim 10\ \mathrm{MW/m^2}$ or smaller on the divertor plates and chamber walls. The roles of recycled hydrogenic atoms and molecules are investigated and distribution of sputtering tungsten throughout the edge region modeled. The simulations are performed with the UEDGE 2D transport code to model both plasma and neutral components with supplementary neutral modeling performed with the DEGAS 2 Monte Carlo code.

1. Introduction

The specification of an FNSF divertor capable of withstanding the high heat flux associated with plasma exhaust is a key element leading to a power plant design [1,2]. A model of this process requires a description of the plasma, neutrals, and radiation on open magnetic field lines, called the scrape-off layer (SOL), that lies outside of the upper and lower X-points for the FNSF magnetic design. The divertor itself is characterized by both the geometry of the plasma-facing components that intersect the magnetic field lines in the vicinity of the separatrix strike points and by the divertor plasma operating-mode controlled by plasma transport, and by sources and sinks of the main-fuel ions (deuterium/tritium [D/T]) and impurity species. Particle sources arise from plasma recycling from material surfaces and gas puffing, and sinks are represented as localized wall pumping regions. The divertor plasma configuration should be designed to spread the heat flux uniformly over a wide area of the plasma-facing components (PFCs) to minimize the peak heat flux.

The need to reduce the peak heat-flux naturally leads to the introduction of strongly radiating impurities that distribute the heat loss isotropically from regions within the plasma via atomic line radiation. In the presence of strong radiation losses, the divertor plasma may be detached, i.e., the plasma power flowing toward the divertor plates is strongly reduced and the local electron temperature falls to about 1 eV where significant electron-ion recombination occurs [3–6]. If the electron temperature falls to the 1 eV range over only a portion of the divertor plate, the plasma is said to be partially detached. Both detachment regimes are explored via edge plasma transport simulations for FNSF. In general, fully detached plasmas have much lower peak heat flux than partially detached plasmas, but the ionization front of the detached plasma may be unstable with respect to migration toward the X-point and consequent degradation of core plasma confinement. Detachment also includes reduction in plasma density and ion saturation current at the target plate via radial transport from turbulence and charge-exchange, and from recombination, but such density reduction is not emphasized here.

The plan of the paper is as follows: The plasma, neutral, and radiation models are described in Sec. 2. In Sec. 3, the implementation of these models in UEDGE [7] is used to predict the heat flux to PFCs for two orientations of the divertor target plates, one tilted toward the magnetic X-point forming a modest angle with the magnetic flux surfaces on both the inner and outer divertor legs and the second with target plates normal to the flux surfaces. These initial solutions use a neutral model where only atomic D/T is evolved directly with recycling molecules being accounted for by an energy transfer from electrons to ion at ionization corresponding to the Franck-Condon dissociation energy. Variations of the SOL and divertor plasmas with divertor leg length and seeded impurity fraction are investigated. In Sec. 4, the

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impact on the plasma solutions of adding an explicit molecular D/T model in UEDGE is investigated and comparisons are made with neutral profiles obtained by DEGAS 2 [8] neutral Monte Carlo code. The detailed impact of atoms and molecules on wall heat fluxes is assessed from the DEGAS 2 results in Sec. 5. The potential impact of sputtering from both plasma and neutral species striking the PFCs in considered in Secs. 4–5, together with the resulting tungsten profiles throughout the SOL. A set of conclusions is given in Sec. 6.

2. Simulation model for the scrape-off layer

The UEDGE transport code [7] is used to model the plasma and neutral gas components as two-dimensional (2D) toroidally symmetric fluids, each characterized by local density, velocity, and temperature. Line radiation from D/T and impurities is also included. The spatial domain includes a portion of the core edge region near the separatrix, the scrape-off layer (SOL) outside the core separatrix, and the private (magnetic) flux regions (PFRs) above and below the X-points. A basic orthogonal flux-surface mesh geometry is shown in Fig. 1. Because cross-field electric and magnetic drifts are neglected for the simulations, the plasma solution is up/down symmetric about a line across the midplane, and only the lower half of the configuration is modeled. The half-space geometry substantially reduces the computational requirements for modeling so efficient parameter scans are possible. For these half-space simulations, some effects of up-down asymmetries can be assessed by considering cases with the power flow into the SOL being less or greater than half of the total power.

2.1. Plasma fluid equations

The structure of the moment equations solved for the plasma can be found in Braginskii [9]. The particle continuity equation

$$\frac{\partial n_j}{\partial t} + \nabla\cdot(n_j \boldsymbol{u}_j) = S_j^p = K_e^i n_e n_n - K_e^r n_e n_i \tag{1}$$

where n_j is the number density, $\boldsymbol{u}_j$ is the mean velocity, and S_j^p is the particle source or sink arising from ionization of neutral particles or recombination of ion-electron pairs. Rate coefficients K_e^i and K_e^r characterize ionization and recombination, respectively. The j index denotes different ion species, and detached plasmas in fusion devices typically involve important contributions from impurity ions, especially in radiative energy loss. The momentum density equation is

$$m_j \frac{\partial n_j \boldsymbol{u_j}}{\partial t} + m_j \nabla\cdot(n_j \boldsymbol{u}_j \boldsymbol{u}_j) = -\nabla P_j + eZ_j n_j (\boldsymbol{E} + \boldsymbol{u}_j \times \boldsymbol{B}) - \boldsymbol{F}_j - \boldsymbol{R}_j + \boldsymbol{S}_j^m, \tag{2}$$

where P_j is the pressure, $\boldsymbol{F}_j$ is the viscous friction force, $\boldsymbol{R}_j$ is the thermal force between charged species, and $\boldsymbol{S}_j^m = K_i^{cx} n_i n_n (\boldsymbol{u}_n - \boldsymbol{u}_i) + K_e^i n_e n_n \boldsymbol{u}_n - K_e^r n_e n_i \boldsymbol{u}_i$ is the momentum source or sink term. The energy density equation

$$\frac{3}{2}\frac{\partial n_j T_j}{\partial t} + \frac{5}{2}\nabla\cdot(n_j \boldsymbol{u}_j T_j) - \boldsymbol{u}_j \nabla P_j = -\nabla\cdot\boldsymbol{q}_j - \boldsymbol{\Pi}_j\cdot\nabla\boldsymbol{u}_j + Q_j + S_j^E, \tag{3}$$

where T_j is the species temperature, $\boldsymbol{q}_j$ is the heat flux, Π_j is the stress tensor, Q_j is the energy exchange between species (ion-electron and ion-neutral), and $S_j^E = (3/2)[K_e^i n_e n_n T_n - K_e^r n_e n_j T_{ij}]$ is an energy source or sink from ionization or recombination for ions, while for electrons, S_e^E refers to energy loss association with excitation, ionization, and recombination collisions. The rates for these electron processes are interpolated from tables compiled as a function of electron temperature and density from the ADAS database [10]. For ions, $Q_i = (3m_e/m_i)\nu_e n_e (T_e - T_i) + (3/2) n_i n_n K_i^{cx} (T_n - T_i)$, where ν_e is given in Ref. [9].

Because of the strong imposed magnetic field, $\boldsymbol{B}$, used in fusion devices, these expressions are generally reduced to those where the cyclotron frequency, $\omega_{cj} = eZ_jB/m_j$, is much larger than τ_j, the Coulomb collision frequency.

Further, only the transport along $\boldsymbol{B}$ is assumed to be governed by classical Coulomb collisions, while that across $\boldsymbol{B}$ is assumed to be larger than classical and governed by plasma turbulence. Thus, the equations are separated into those describing transport along $\boldsymbol{B}$, referred to as the parallel direction denoted by the ||-subscript, and the perpendicular direction, denoted by the ⊥-subscript. The perpendicular direction has two components, one across magnetic flux surfaces and a second lying within the flux surface. For plasma transport modeling, the perpendicular direction general means the component across magnetic flux surfaces. However, for 3D turbulence modeling, the second component within the flux surface is important and needs to be retained.

The momentum equation for the ion parallel velocity, $u_{\|j}$, can thus be written as

$$m_j \frac{\partial n_j u_{\|j}}{\partial t} + m_j \nabla\cdot(n_j u_{\|j} \boldsymbol{u_j}) = -\nabla_{\|} P_j + eZ_j n_j E_{\|} - F_{\|j} - R_{\|j} + S_{\|j}^m. \tag{4}$$

For electrons, owing to their small electron mass, the inertia terms on the left-hand side and the viscous forces plus momentum sink/source terms can be neglected, yielding the simpler electron momentum equation (with $j \rightarrow e$)

$$0 = -\nabla_{\|} P_e - e n_e E_{\|} - R_{\|e}. \tag{5}$$

This equation can be used to compute $E_{\|}$ from plasma quantities. For a singly-ionized plasma with $Z_i = 1$ (so $n_i = n_e$ where we take $j{=}i$), the electron thermal force is given by [9]

$$R_{\|e} = -c_{re}\frac{m_e}{\tau_e}\frac{J_{\|}}{e} + c_{te} n_e \frac{\partial T_e}{\partial s_{\|}}, \tag{6}$$

where $J_{\|} = e n_e (u_{\|i} - u_{\|e})$ is the parallel current, $s_{\|}$ is the distance along $\boldsymbol{B}$, $c_{re} \approx 0.51$, and $c_{te} \approx 0.71$. For the up/down symmetric geometry considered here, $J_{\|} = 0$.

In the perpendicular direction, we also assume that the plasma particle fluxes are ambipolar, i.e., the same for ions and electrons. The simplified form taken is typically

$$\Gamma_n = n_i u_{\perp a} = -D_{an}(r)\frac{\partial n_i}{\partial r} + n_i u_c(r), \tag{7}$$

where D_{an} is an anomalous (turbulence driven) diffusion coefficient, and $u_c(r)$ is an anomalous convective velocity, chosen to fit

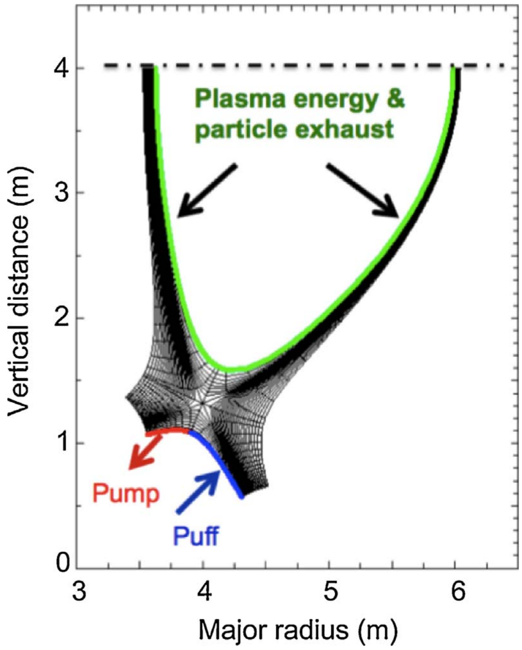

Fig. 1. Lower-half FNSF domain used for edge-region simulations.